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Diagnostic Aids for Military Systems

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Abstract
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As you may be aware, Rand has done considerable work for t he Air Force in several areas related to diagnostic aid systems, such as investigations of engine health monitoring systems and studies of aircraft maintenance policies and programs. Recently, Rand has undertaken, under ARPA sponsor ship, a project to assess the utility and cost-effectiveness of diagnostic aid systems for U.S. Army ground vehicles. My examples will be drawn from the findings of this study. The relationship between diagnostic aid systems and NO[is left as an exercise for the reader.

Disciplines
Engineering Science and Materials | Structures and Materials

DIAGNOSTIC AIDS FOR MILITARY SYSTEMS

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As you may be aware, Rand has done considerable work for the Air Force in several areas related to diagnostic aid systems, such as investigations of engine health monitoring systems and studies of aircraft maintenance policies and programs. Recently, Rand has undertaken, under ARPA sponsorship, a project to assess the utility and cost-effectiveness of diagnostic aid systems for U.S. Army ground vehicles. My examples will be drawn from the findings of this study. The relationship between diagnostic aid systems and NDE is left as an exercise for the reader.

The utility of diagnostic aid systems can be reflected in increased operational readiness for various kinds of military equipment, as well as increased maintenance efficiency. I'm sure you have heard these words before, and I'll discuss these themes subsequently.

I have to thank Don Thompson for the idea for the first figure (Fig. 1) "Diagnostic Aid Systems (Theory)." I realize it's a gross exaggeration to say that this figure shows the theory of diagnostic aid systems. Of course, it merely suggests the idea behind them: that is, that somehow, using a diagnostic parameter, some measured characteristic of a system can be related to the state or status of the system. Hopefully, a healthy system can be distinguished from a system that is in some stage of failing, and a system that has failed. This also applies to a sub-system or component.

A diagnostic aid system can be defined as being made up of three subsystems (see Fig. 2): a sensing subsystem, whose function is obvious; an information processing and display subsystem; and finally, a failure model (see Fig. 3). Many people raise the question, "What are you doing calling a failure model a subsystem of a diagnostic aid system?" Well, I think it's the most important component of the diagnostic aid system.

This is the rationale: The failure model defines failure (at least our interpretation of failure) and also establishes the fundamental limits of error of the system. This provides guidance for the design and use of diagnostic aid systems, including deciding what to do with the data and what kind of repair or replacement action to take.

DIAGNOSTIC AID SYSTEMS (THEORY)

FIND DIAGNOSTIC PARAMETER(S) WHICH CAN BE RELATED TO EQUIPMENT CONDITION AND TO SOME SENSED CHARACTERISTIC(S) OF THE EQUIPMENT, ITS SUBSYSTEM(S) AND/OR COMPONENTS

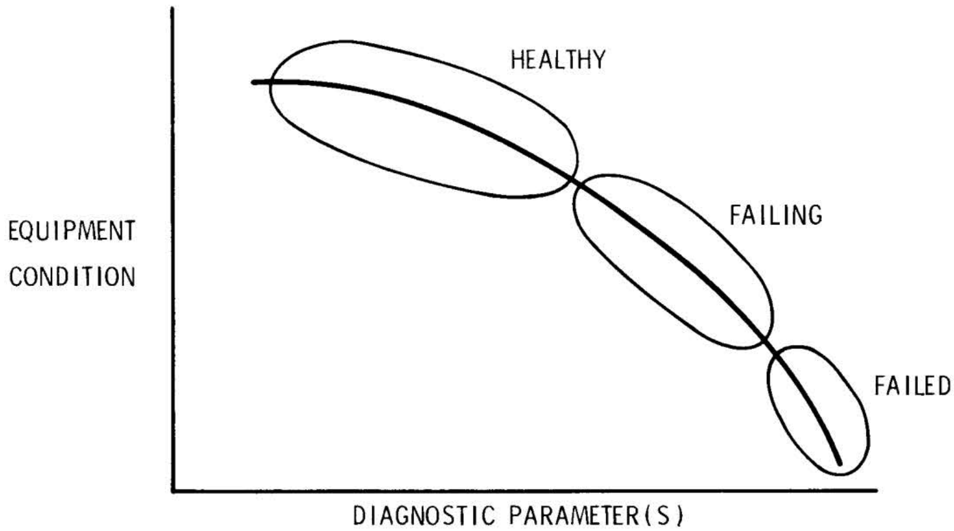


Fig. 1. Schematic representation of equipment condition characterization by diagnostic aid systems.

DIAGNOSTIC AID SYSTEM

SUB-SYSTEM	FUNCTION
• SENSING	DETECT/MEASURE CHARACTERISTIC(S) RELATED TO DIAGNOSTIC PARAMETER(S)
• INFORMATION PROCESSING/DISPLAY	COLLECT, CONVERT AND DISPLAY SENSING SUBSYSTEM OUTPUT INTO DIAGNOSTIC PARAMETER(S) UNITS
• FAILURE MODEL(S)	RELATE DIAGNOSTIC PARAMETER(S) TO FAILURE

Fig. 2. Subsystem of diagnostic aid systems and their functions.

FAILURE MODEL

- CRITICAL PART OF DIAGNOSTIC AID SYSTEM
  - DEFINES FAILURE(S) - RELATES DATA TO ACTION
  - PROVIDES DESIGN/USE GUIDANCE
  - DETERMINES ERROR RATES
- TYPES
  - THEORETICAL - PHYSICS, ENGINEERING ESTIMATES, INTUITION
  - EMPIRICAL - FAILURE DATA
- PROBLEMS
  - MOST MODELS ARE INTUITIVE OR ENG. ESTIMATES
  - MOST MODELS DERIVED FROM FAILURE DATA ARE BASED ON FAILURE RATES NOT MODES
  - FAILURE RATES OFTEN EQUATED TO REPLACEMENT RATES

Fig. 3. Failure model elements.

Failure models can be theoretical or empirical. Theoretical models may, very rarely, be derived from the fundamental physics of the equipment, but usually are derived from engineering estimates. By this we usually mean design specifications--which are often estimates--and intuition. In some of these areas we're looking at, such as Army ground vehicles, engineering estimates turn out to be a major source of failure models. Empirical models are usually based on failure data. And the problem we have with them is that the models are derived from failure rate and not from failure modes. So you know how many units failed, but you don't know exactly what components are failing. Worse than that, the so-called failure rate data are often replacement rate data, which gives little information about the cause of failure. For example, the favorite way of fixing Army ground vehicles is repair by replacement, so if you count replaced parts and use the replacement rates to formulate failure models, you can be off by nearly an order of magnitude in some cases.

In Fig. 4, I've arranged various functions of diagnostic aids in what seems to be a logical order, all the way from failing and failure detection to fault isolation and health monitoring, up to failure prediction. Experience so far indicates that, as you go up the ladder from fault isolation to failure prediction, the diagnostic systems become increasingly complex, with greater requirements for data, for information processing and display, etc. I personally don't believe that this is the way things have to go. In fact, several efforts are underway to work out some sort of diagnostic aid, for health monitoring, for example, that is relatively simple, perhaps based on the infrequent measurement of one or two characteristics and using one diagnostic parameter. However, that is a hope for the future. The history to date is one of increasing complexity.

And finally, let me emphasize that a failure model should not be cast in concrete and then forever used as the bible, but should be altered as you learn more and more about the system being diagnosed.

Now, let's discuss some issues--which are really preliminary conclusions of my work, but since they require further supporting evidence, we'll call them issues (see Fig. 5).

First of all, hardware technology doesn't seem to be the problem. It's clear that we need better and cheaper hardware; we need cheaper and more reliable transducers, for instance. However, all the technology we really need seems to be available, except the technology relating to failure models. I realize that this is extending the word "technology" perhaps past what is usual, but, in my view, failure models are a part of technology, and there's a lot of work that needs to be done in this area.

Relating monitored characteristics to diagnostic parameters is also a serious problem, the typical difficult software problem. As a result, I feel that the system engineering and general technical direction of diagnostic aid systems has been inadequate and has produced more confusion than satisfaction. In recent months there have been attempts to justify diagnostic aid

DIAGNOSTIC AID SYSTEMS

FUNCTION	SENSING	INFO. PROCESSING/ DISPLAY	FAILURE MODEL
FAILURE PREDICTION			
HEALTH MONITORING	MORE SENSORS	MORE DATA	BETTER MODELS
FAULT ISOLATION	BETTER SENSORS	MORE PROCESSING	MORE COMPLEX
	MORE SAMPLES	MORE DETAILED DISPLAYS	BETTER DATA BASES
FAILING/FAILURE DETECTION			

Fig. 4. Functions of diagnostic aid systems.

ISSUES

- TECHNOLOGY IN TERMS OF HARDWARE (SENSORS, PROCESSORS, DISPLAYS) IS NOT THE PROBLEM NOW
- TECHNOLOGY IN TERMS OF STATE-OF-THE-ART IN FAILURE MODELS IS A SERIOUS PROBLEM
- RELATING MONITORED CHARACTERISTIC TO DIAGNOSTIC PARAMETERS IS ALSO A SERIOUS PROBLEM
- SYSTEMS ENGINEERING AND TECHNICAL DIRECTION (AS A RESULT OF ABOVE) HAVE BEEN GENERALLY INADEQUATE
- COST EFFECTIVENESS ANALYSES HAVE BEEN TOO NARROW AND BASED ON TENUOUS ASSUMPTIONS
- REAL COST EFFECTIVENESS LIES IN REDUCING INVENTORIES, INCREASING UTILIZATION AND REDUCING MAINTENANCE MANPOWER, EQUIPMENT AND FACILITIES
- BROAD VIEW OF UTILITY HAS NOT BEEN TAKEN
  POST PRODUCTION CHECKS ⟶ DAMAGE ASSESSMENT

Fig. 5. Key issues in the application of diagnostic aid systems.

systems on the basis of cost-effectiveness studies. I've looked at several of these studies and have concluded that generally they have been too narrow and based on very tenuous assumptions. All of them are based on the assumption that failure rates equal replacement rates, which I've discussed earlier. And studies repeatedly conclude that diagnostic aids are cost-effective because they save the replacement of good components or subsystems. However, my view is that the use of diagnostic aid systems and NDE can, in fact, have a much greater impact than just saving good parts. It can cause major changes in maintenance structures and modes. It can even change operational modes for equipment. I believe that true cost-effectiveness of diagnostic aids lies in reducing inventories, increasing utilization, and reducing maintenance manpower, equipment, and facilities.

As far as equipment life and usage goes, the point here is that if we are going to talk about diagnostic aid systems for a particular set of military equipment, we'd better take a good look at that military equipment first. Certain classical "age" indicators, such as vehicle mileage, may or may not be valid indicators, depending on the level of vehicle usage. Many diagnostic aid systems have been designed for high mileage vehicles, yet the average annual mileage for a 2½-ton Army truck is less than 2000. It turns out that mileage, which is often thought of as a good diagnostic parameter, is good only for high usage, high mileage vehicles. With low mileage vehicles, vehicle failures are more closely related to the number of engine starts than to the miles driven. (See Fig. 6.) For tanks, it turns out that tank failures may be related more closely to the number of times the gun was fired than to either the mileage or the engine starts. The message is clear: Take a good look at the equipment and how it's being used before selecting the diagnostic parameters.

In looking at the life phases of Army vehicles (Fig. 7) we find that diagnostic aids play different roles at different phases of the life cycle. They have greater utility than their maintenance orientation. An important function is postproduction checks. By this, I mean not only diagnosis of newly acquired equipment, but using a diagnostic aid system to check the unit after any design change introduces a new component or subsystem. By identifying faulty components and interactions early, such postproduction checks can prevent unhealthy systems from entering the inventory, and reduce the introduction of less reliable parts.

It turns out that Army acquisition of unhealthy vehicles produces maintenance nightmares from the day they arrive. There hasn't been a really good way to figure this out until things start failing--and usually, with this type of vehicle, it isn't a case of a single failure; many things fail in rapid succession. Also, there have been many occasions when the services have bought what is supposed to be a more reliable part or substance, and in reality they've acquired a less reliable one. In fact, the Army recently finished testing its new so-called "5000-mile tank tread", which actually goes about 500 miles--5000 mile design, 500 mile actual performance. So there is a case to be made for using diagnostic aid systems to reduce this kind of problem.

VEHICLE ACTIVITY LEVELS

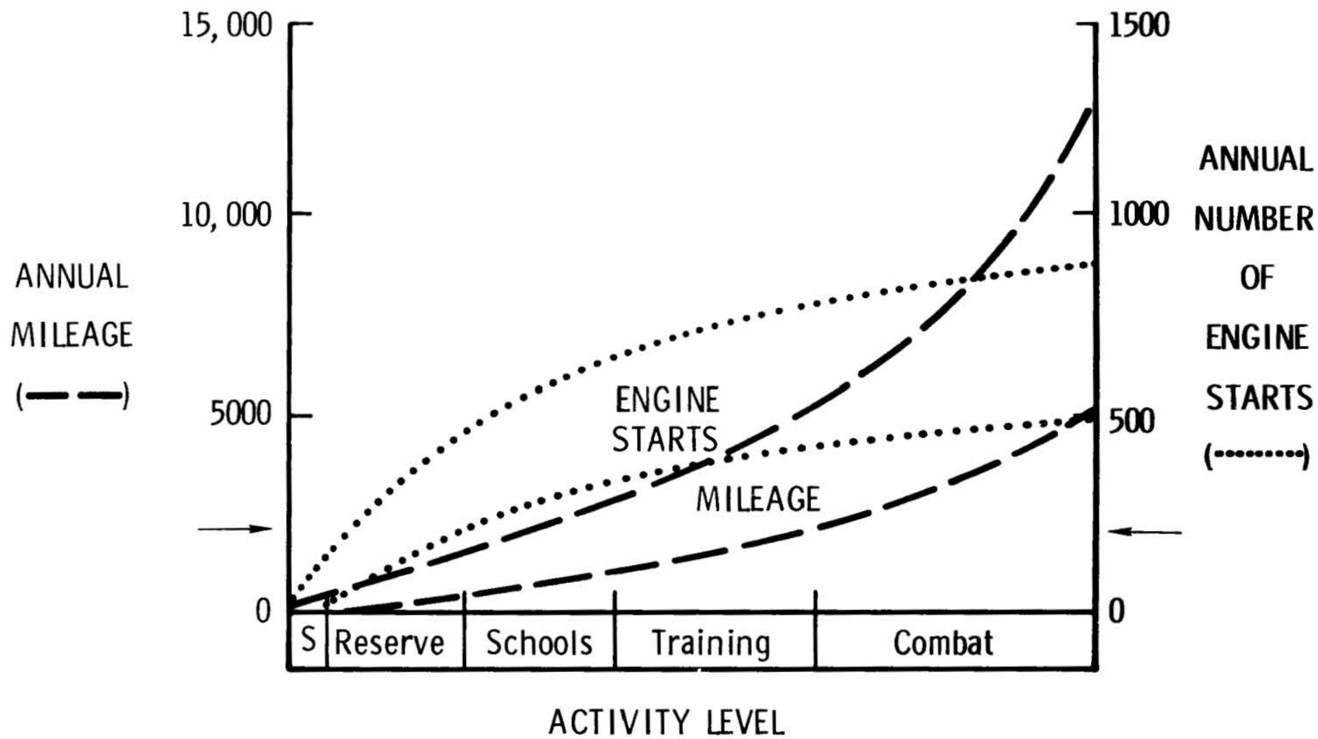


Fig. 6. Engine start and mileage characteristics for 2-1/2 ton Army trucks in various operation modes. The arrow indicates the average annual mileage.

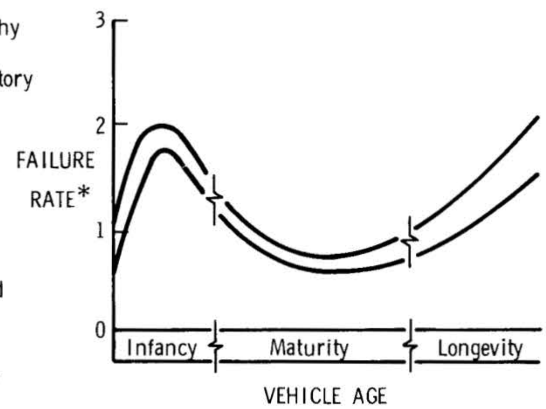
VEHICLE LIFE PHASES

INFANCY

POST PRODUCTION CHECK

TO -

- Prevent Unhealthy Systems from Entering Inventory
- Identify Faulty Components and Interactions Early
- Establish Early History of Subsystems and Components
- Reduce Introduction Rate of Less Reliable Parts



*Normalized to Design Rates

MATURITY AND LONGEVITY

PERIODIC AND ON-DEMAND CHECKS

TO -

- Reduce Unscheduled Maint./Repair Actions
- Extend Scheduled Periods Maint./Repair Actions
- Verify Maint./Repair Actions
- Reduce Secondary Failures
- Continue History

Fig. 7. Life phases of Army vehicles.

Also, a diagnostic aid system may turn out to be one of the best data collection tools you have for finding out what really happens to a piece of equipment. I'll go into this in more detail later.

In the maturity/longevity phase of equipment life, diagnostic aids are used in the ways more commonly thought of, to reduce unscheduled maintenance and repair actions and to extend scheduled maintenance intervals. An important use is to verify maintenance and repair actions. We've noticed particularly in some Army vehicles, that whenever something fails and is repaired, it fails again roughly twice as fast, and fails three times as fast the third time. One has to ask whether or not the initial repair action is bringing the system back to anywhere near its original condition.

A major problem is that many of the failure data collection activities revolve around the operator of the equipment or the people who perform the maintenance on it, and these people are graded as an operator on how many times the truck fails or doesn't fail. So, they are not exactly inspired to report all failures faithfully. The same thing happens with the maintenance personnel. If they are asked to report their diagnostic activities without any kind of checking or overview, they're wonderful; they can diagnose anything, anywhere, any time. But it doesn't happen that way.

These biases are not present with the diagnostic aid system, and therefore, it provides more accurate and reliable data on which to build and refine failure models. To repeat an important point about failure models, they should not be set in concrete and then used forever as the Bible, but should be designed to be modifiable as you learn more and more about the system. If they are not readily alterable, problems will develop.

There are also human engineering problems--such as digital versus analog displays. Everything I've seen so far says go digital. Particularly when you're dealing with systems which involve as many as 25 different measurements, all of which are taken on different scales. It's similar to the old multivoltmeter problem where you have a needle running across several different scales and you've got to figure out which scale to use. From a user orientation, digital displays, which automatically read out in units of the appropriate scale, are highly preferred.

Maintenance manuals are an old problem. Let me reiterate what I'm sure you've heard many times, that the guy in the field can't read technical documentation. He needs something simple, clear, explicit, and written in user language.

Now, the diagnostic orientation runs squarely up against much of the maintenance training activity in the Army: people are trained to replace things, not to find out what's wrong with them. And so, it's going to require newer kinds of training to get people to really think as troubleshooters.

As part of our project, we are looking at commercial diagnostic aid systems, and I'm beginning to question the need for military specs across the board. Some commercial diagnostic aid systems I've investigated look as though they could go right into the military inventory without any redesign to military specs, which, of course, can increase the price by an order of magnitude. A problem here is trying to interest commercial vehicle suppliers in diagnostic aid systems. The commercial R&D people have a minimal interest in diagnostic aid systems, because their motivation is very much tied to keeping vehicle costs as low as possible. However, I have been talking with them, trying to point out that lowering lifetime costs can be a strong selling point. What I'm trying to do is excite some of the people in commercial R&D to get more into the diagnostic aid business. They have far more R&D resources to do this, of course, than the Government does.

Both in the Air Force and in the Army the diagnostic aid systems that now exist have reliability and maintainability problems. Across the board, the systems existing today do not have acceptable reliability. A lot of it is what I call front end problems--that is, the problem is not in the processor, it's in the transducers, and the leads to the transducers, and that kind of area. This seems to be something that can be corrected simply by better design and manufacturing techniques. Also, diagnostic aid systems ought to include self-test features. One of the real problems in using a diagnostic aid system is knowing the operability of the system itself. This has been a neglected feature.

Figure 8 summarizes the main issues discussed here. There are many payoff areas for diagnostic aid systems, including saving parts, changing maintenance structures, reducing personnel, reducing equipment inventories, and increasing utilization of equipment. These benefits are obvious, in a sense, but difficult to treat analytically. The reason is the difficulty of getting accurate and meaningful data--operational, maintenance, and cost data, as well as manpower data.

Failure models are just not well developed, and in some cases diagnostic aid systems are really R&D hobby items. People have built them because they test and measure things, and when they measure enough things, they lead you to some sort of tentative conclusion that something is wrong. The only problem is that when you put them to a test, it turns out that they tell you that all kinds of things are wrong that aren't, and they don't tell you certain things that really are wrong.

We need "smart" data, not more data. Whenever you get into a study that touches on maintenance, there's a tendency to want to collect an awful lot of data, and indeed there are large data collections sitting around. Some of them will forever be sitting around because you can't get into them to get the information you want, or else the data is not reliable or accurate enough. Let me say that I am a firm believer that when any data

SUMMARY

- HIGH PAYOFF AREAS IN THE APPLICATIONS OF DIAGNOSTIC AIDS ARE OBVIOUS BUT DIFFICULT TO TREAT ANALYTICALLY
- THE TECHNOLOGY OF DIAGNOSTIC AID SYSTEMS—PARTICULARLY FAILURE MODELS IS NOT WELL DEVELOPED
- MEANINGFUL STUDIES OF THE EFFECTIVENESS AND COSTS OF DIAGNOSTIC AID SYSTEMS REQUIRE CAREFUL CONSIDERATION OF MAINTENANCE STRUCTURES, MODES AND COSTS
- STUDIES TO DATE HAVE BEEN TOO NARROW IN SCOPE AND APPROACH
- "SMART" NOT LARGE DATA COLLECTION EFFORTS ARE NEEDED

Fig. 8. Summary of the status of diagnostic aid systems.

collection system is being designed, the analyst should be in at the front end to reflect on what kind of data will be valuable and what form it should be in. Otherwise, the design engineers may make provisions to give you all the data they can possibly think of, and it may not be what you need.

And finally, in this ARPA-sponsored activity, we are trying to find out if there is a high payoff for increased RDTE investments in diagnostic aid systems, and, if so, where should the RDTE dollars go.

DISCUSSION

DR. DON THOMPSON (Science Center, Rockwell International): Thank you very much, Bill.

DR. PAUL PACKMAN (Vanderbilt University): Not necessarily a question but a comment regarding this NDT data base. There is a tremendous amount of data available for quantitative evaluation for detection sensitivity.

DR. WHELAN: Well, as I said earlier, the relationship between diagnostic aid systems and NDE is the exercise for the listener. What I am concerned about is that people are trying to measure all kinds of failures in large complicated subsystems of amazingly complex systems. For a lot of the components in those subsystems, a good NDE technique doesn't exist or nobody has looked at that component to see what it is made of. So I am concerned that these diagnostic aid systems may be biting off a lot more than they can really handle.

I am sure that the data problems that you refer to exist in diagnostic aid systems as well as in the NDE activities you mention. Someone has collected data for a certain problem, and when you try to apply it to another problem, you find out that certain pieces of the data are not useful and usually you need something that was not collected originally.

COL. RON NOKES (Kelly Air Force Base): I gather your study is more oriented toward the management line of diagnostics. It's not really going to get into the final details technically. It would appear to me that there's a lot of engine diagnostic systems on aircraft engines and they're all in competition with each other. There doesn't appear to be any single organization that has taken a look at the whole picture.

DR. WHELAN: That's what I came to very quickly. I started out looking at individual automotive engine diagnostic aids, and backed off, saying that the problem is bigger than just one of these systems.

COL. RON NOKES: You can go further than that, because there are several aircraft engine diagnostic systems that are being procured now?

DR. WHELAN: Yes, the Army recently has taken an interesting step by forming a Department of the Army--I stress that to show you it's up high enough--a Department of the Army Central TMDE Product Management Office (TMDE standing for Test, Measurement and Diagnostic Equipment). The Army regulation creating this office gave it broad powers, causing several problems. For example, it implied that the TMDE people have the authority to veto the procurement of a system if it doesn't have adequate TMDE equipment. Now, the first time they tried to exercise that, they got thrown out of the room. But it's interesting that that kind of activity is being centralized and they're worried about the proliferation of diagnostic, test, and measurement equipment.

COL. RON NOKES: When will you have a final report on the efforts you're doing?

DR. WHELAN: About the end of the year.

DR. DON THOMPSON: One more question.

MR. STUHRKE (Martin-Marietta): We have a program at Martin that I think is worth commenting on here. We had a program with Rome Air Development Center for about six to eight years on component reliability and it bears on what you're talking about.

We've taken an approach a little bit different from what yours is. We go into a system, do a fault free analysis on it where you determine what are the critical parts. Then we develop data on these critical parts and their failure rate. Now, at the very base level with an electronic component, for example, its a go/no-go affair if the transistor fails or it doesn't, and we've developed these data in reliability handbooks.

The program is being sponsored by Mr. Winzikowski at Rome Air Development Center and these reports are available. We've applied these programs and developed actual equations which would predict failures, which look just like yours. You know, you have the infant mortality, when you have a nice area where very little happens and then through old age it begins to break down and we have applied this basically to the Sprint system which, as you're aware, is now in the field.

We predicted, based on these reliability numbers which take into account both a dormant state and active state for different reliability numbers, and were able to pr dict very closely the reliability availability of the system. In other words, out of a hundred missiles, if I pushed the button, what probability do I have the thing will work? Not only will it work, will it hit the target? And this has worked very well going at it from the very bottom.

Now, you mentioned another aspect, too, the commercial aspect. We have been working with several of the automotive companies at the component level again. It was announced very recently, for example, that Chrysler this year is going to be building an electronic engine. They're putting a sealed PC board system into the motor, which will control the spark, the spark advance and all of these sorts of things. We have been working with them to evaluate the types of reliability that they need to determine how many of these they have to have out in the field and just the whole maintenance cycle.

We're developing this reliability number based on the reliability of the individual component and also how they go together, and, in contrast to one of the things you said, we need lots of data rather than smart data. We found in this six to seven year system what we need is lots and lots of data. We're talking about hundreds of millions of part hours.

Also, there is another component program which looks at mechanical reliability where we've gone around to various aircraft companies and the airlines, primarily, to get data on the failure of their mechanical systems. For example, a landing gear actuator system. Did the cylinder fail, did the bearing fail, did the hydraulic line fail; and we're developing part hour data on this which will come out in about a year.

I think this is an alternative approach to looking at the big things, to start from the bottom. My only comment is that it really works, and I think that we need to look at this approach as well.

DR. WHELAN: I think it's a very valid alternative approach that you've just pointed out. Certain operational problems in the military service are causing people to want to do something in a very immediate sense, but I think both approaches should certainly go on and we should talk about it sometime.